

Production of the charged Higgs bosons at the CERN Large Hadron Collider in the left-right symmetric model

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We study the production of the charged Higgs boson at the LHC in the left-right symmetric model. It is shown that there exists a lower bound of the cross section. We investigate that predicted cross sections of this model are generally larger than those of the two Higgs doublet model or the minimal supersymmetric model.

I. INTRODUCTION

Search of Higgs bosons is the primary goal of the CERN Large Hadron Collider (LHC). In the standard model (SM), one neutral Higgs boson exists as a result of the electroweak symmetry breaking (EWSB), of which mass is not predicted in the theoretical framework. The discovery potential for the SM Higgs boson at the LHC will reach to about 1 TeV with the integrated luminosity of 100 fb^{-1} . It implies that the SM Higgs boson will be discovered at the LHC at more than $5\text{-}\sigma$ level. In many models of new physics beyond the SM, however, more symmetries are involved and the Higgs sector should be extended to break larger symmetry. Signatures of an extended Higgs sector would provide direct evidence for new physics beyond the SM. Models with an extended Higgs sector often contain charged Higgs bosons H^\pm , which do not exist within the SM.

The two Higgs doublet model (2HD) is one of the simplest extension of the SM and the Higgs structure of the minimal supersymmetric standard model (MSSM). There are three neutral Higgs bosons, h^0 , H^0 , A^0 and a pair of charged Higgs bosons H^\pm in the 2HD model and the MSSM. Hereafter the 2HD model and the MSSM are just called the 2HD model generically. If the H^\pm bosons are lighter than the top quark, they can be produced in the top quark decay processes $t \rightarrow bH^\pm$. Search for H^\pm from top quark decays in the 2HD model has been performed at Tevatron and no evidence for H^\pm production is found [1]. The CERN Large Electron Positron Collider (LEP) has also examined the charged Higgs bosons up to $\sqrt{s} = 200 \text{ GeV}$ through the pair production of H^\pm to present the lower bound of the charged Higgs boson mass [2, 3]. Recent measurement of $\text{Br}(B^\pm \rightarrow \tau\nu)$ by Belle provides indirect constraints on the charged Higgs bosons in the 2HD model via the annihilation diagram mediated by H^\pm boson [4, 5]. The absence of the observed charged Higgs boson so far derives constraints on $(\tan\beta, m_{H^\pm})$ parameter space for the 2HD model. If the charged Higgs bosons are heavier than the top quark, we have to observe the direct production at hadron colliders. The most promising channel for the charged Higgs boson production at the LHC is the $gb \rightarrow tH^\pm$ process which has been extensively studied [6, 7, 8, 9]. The Drell-Yan mechanism $gg, q\bar{q} \rightarrow H^-H^+$ and the associated production with a W boson, $q\bar{q} \rightarrow H^\pm W^\mp$ are suppressed due to the weak couplings, low quark luminosity, and loop suppression. The discovery potential of the H^\pm bosons at the LHC has been studied by ATLAS [10] and CMS [11] groups. Expected to be discovered is a MSSM charged Higgs boson as heavy as 1 TeV at the $5\text{-}\sigma$ confidence level, or may be excluded up to the mass of 1.5 TeV at 95 % C.L. at the LHC with the MSSM radiative corrections [9].

The left-right (LR) symmetric model based on the gauge symmetry, $\text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)_{B-L}$, usually contain a bidoublet Higgs field $\phi(2, \bar{2}, 0)$ for the EWSB and the Yukawa couplings represented by

$$\phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}. \quad (1)$$

since both of the right-handed fermions and the left-handed fermions transform as doublets under $\text{SU}(2)_R$ and $\text{SU}(2)_L$ [12]. The additional $\text{SU}(2)_R$ gauge symmetry should be broken by another Higgs sector at the scale much higher than the electroweak scale [13, 14, 15, 16]. The weak scale phenomenology of the Higgs sector is principally determined by the bidoublet Higgs fields, and the dominant field contents are similar to those of the 2HD model: h^0 , H^0 , A^0 and

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H^\pm . However, the structure of the Yukawa couplings and potential of the bidoublet Higgs fields are much different from those of the two doublet Higgs fields. Therefore, it leads to different charged Higgs boson phenomenologies from those in the 2HD model. Constraints on the charged Higgs boson parameter space in the LR model with the present experimental data from Tevatron, LEP and Belle has been presented in Ref. [17]. In this work, we explore the production of H^\pm bosons at the LHC in the LR model. This paper is organized as follows: In section 2, we briefly review the Higgs sector of the LR model. The production cross sections at the LHC are presented in section 3 and we conclude in section 4.

II. THE HIGGS SECTOR OF THE LEFT-RIGHT SYMMETRIC MODEL

The left-right symmetric model involves an additional $SU(2)_R$ symmetry which has to be broken at the higher scale than the electroweak scale. Two triplet Higgs fields $\Delta_L(3, 1, 2)$ and $\Delta_R(1, 3, 2)$ represented by

$$\Delta_{L,R} = \frac{1}{\sqrt{2}} \begin{pmatrix} \delta_{L,R}^+ & \sqrt{2}\delta_{L,R}^{++} \\ \sqrt{2}\delta_{L,R}^0 & -\delta_{L,R}^+ \end{pmatrix}, \quad (2)$$

are introduced to break the additional symmetry of the model. Actually Δ_R breaks the $SU(2)_R$ symmetry and another triplet Δ_L is just introduced as a result of manifest left-right symmetry. The kinetic terms for Higgs fields are given by

$$\mathcal{L} = \text{Tr} [(D_\mu \Delta_{L,R})^\dagger (D^\mu \Delta_{L,R})] + \text{Tr} [(D_\mu \phi)^\dagger (D^\mu \phi)], \quad (3)$$

where the covariant derivatives are defined by

$$\begin{aligned} D_\mu \phi &= \partial_\mu \phi - i \frac{g}{2} W_{L\mu}^a \tau^a \phi + i \frac{g}{2} \phi W_{R\mu}^a \tau^a, \\ D_\mu \Delta_{L,R} &= \partial_\mu \Delta_{L,R} - i \frac{g}{2} [W_{L,R\mu}^a \tau^a, \Delta_{L,R}] - i g' B_\mu \Delta_{L,R}. \end{aligned} \quad (4)$$

The spontaneous breaking of gauge symmetries is triggered by the vacuum expectation values (VEV)

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix}, \quad \langle \Delta_{L,R} \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}. \quad (5)$$

The $SU(2)_R$ breaking scale v_R should be higher than the electroweak scale, $k_{1,2} \ll v_R$ since W_R should be heavier than W_L . Note that v_L is irrelevant for the symmetry breaking and just introduced in order to manifest the left-right symmetry. The see-saw relation for the neutrino mass $m_\nu \sim M_{LL} + M_{LR}^2/M_{RR}$ tells us that v_R is typically very large $\sim 10^{11}$ GeV, where M_{ij} are the matrix elements for the masses in the (W_L, W_R) basis. Then the heavy gauge bosons are too heavy to be produced at the accelerator experiments and the $SU(2)_R$ structure is hardly probed in the laboratory. Provided that v_R is assumed to be only moderately large $v_R \sim \mathcal{O}(\text{TeV})$ for the heavy gauge bosons to be studied at LHC, the Yukawa couplings require to be suppressed in order that the neutrino masses are at the eV scale and v_L should be very small or close to 0. This is achieved when the quartic couplings of $(\phi\phi\Delta_L\Delta_R)$ -type terms in the Higgs potential are set to be zero [18, 19]. This limit is warranted by the approximate horizontal $U(1)$ symmetry [20] as well as the see-saw picture for light neutrino masses. We adopt this limit here. Higgs boson masses are not affected by taking this limit [19].

The general Higgs potential in the LR model has been studied in Refs. [18, 19, 21]. We define the parameters $\xi = k_2/k_1$ and $\epsilon = k_1/v_R$ for convenience. The parameter ξ is the ratio of two VEVs for the EWSB which is corresponding to $\tan \beta$ in the 2HD model. Since $\epsilon \ll 1$, we will present our formulas as powers of ϵ . Taking the limit that the quartic couplings for $(\phi\phi\Delta_L\Delta_R)$ terms and v_L go to 0 as mentioned above, the charged Higgs boson mass matrix is given in the basis of $(\phi_1^+, \phi_2^+, \delta_R^+, \delta_L^+)$ by

$$\mathcal{M}_+^2 = \begin{pmatrix} m_+^2 & m_+^2 \xi & m_+^2 \epsilon (1 - \xi^2)/\sqrt{2} & 0 \\ m_+^2 \xi & m_+^2 \xi^2 & m_+^2 \epsilon \xi (1 - \xi^2)/\sqrt{2} & 0 \\ m_+^2 \epsilon (1 - \xi^2)/\sqrt{2} & m_+^2 \epsilon \xi (1 - \xi^2)/\sqrt{2} & m_+^2 \epsilon^2 (1 - \xi^2)^2/2 & 0 \\ 0 & 0 & 0 & m_{\rho_3}^{(+)^2} \end{pmatrix}, \quad (6)$$

where $m_+^2 = \alpha_3 v_R^2/2(1 - \xi^2)$ with the quartic coupling α_3 for $\text{Tr}(\phi^\dagger \phi \Delta_L \Delta_L^\dagger) + \text{Tr}(\phi^\dagger \phi \Delta_R \Delta_R^\dagger)$ term [19]. If $\xi > 1$, α_3 should be negative to avoid the dangerous negative mass square of scalar fields. Note that δ_L^+ field from the Higgs

triplet Δ_L decouples from other three charged Higgs fields with mass $m_{\rho_3^{(+)}}^2$ and is irrelevant for our phenomenological discussion here. The mass of the lightest charged Higgs boson is given by

$$m_{H^\pm}^2 = m_+^2(1 + \xi^2) \left(1 + \frac{1}{2}\epsilon^2 \frac{(1 - \xi^2)^2}{1 + \xi^2} \right), \quad (7)$$

after diagonalization. Since m_{H^\pm} depends on the coupling α_3 , it is an independent observable. Thus the charged Higgs phenomenologies are expressed in terms of two parameters ξ and m_{H^\pm} . Note that the mass of W_R boson does not appear at the charged Higgs phenomenology. No CP violation in the Higgs sector is assumed for simplicity.

Violating the lepton numbers and baryon numbers, the triplet Higgs fields do not allow the ordinary Yukawa coupling terms for Dirac fermions. Thus quark and lepton masses are derived from the Yukawa couplings in terms of the bidoublet Higgs fields, given by

$$\mathcal{L} = \bar{\Psi}_L^i \left(\mathcal{F}_{ij} \phi + \mathcal{G}_{ij} \tilde{\phi} \right) \Psi_R^j + H.c., \quad (8)$$

where $\Psi^i = (\hat{U}, \hat{D})^\dagger$ is the flavour eigenstates, $\tilde{\phi} = \tau_2 \phi^* \tau_2$, and \mathcal{F}, \mathcal{G} are 3×3 Yukawa coupling matrices. We rotate \hat{U} and \hat{D} into the mass eigenstates by unitary transforms, $\hat{U}_{L,R} = V_{L,R}^U U_{L,R}$ and $\hat{D}_{L,R} = V_{L,R}^D D_{L,R}$, to define Cabibbo-Kobayashi-Maskawa (CKM) matrix $V_{L,R}^{CKM} = V_{L,R}^{U\dagger} V_{L,R}^D$. We assume the manifest left-right symmetry $V_L^{CKM} = V_R^{CKM}$. The Yukawa coupling matrices \mathcal{F} and \mathcal{G} are given in terms of

$$\begin{aligned} \mathcal{F} &= \frac{\sqrt{2}}{k_-^2} \left(k_1 V_L^U \mathcal{M}^U V_R^{U\dagger} - k_2 V_L^D \mathcal{M}^D V_R^{D\dagger} \right), \\ \mathcal{G} &= \frac{\sqrt{2}}{k_-^2} \left(-k_2 V_L^U \mathcal{M}^U V_R^{U\dagger} + k_1 V_L^D \mathcal{M}^D V_R^{D\dagger} \right), \end{aligned} \quad (9)$$

where $k_-^2 = |k_1|^2 - |k_2|^2$ and \mathcal{M}^U and \mathcal{M}^D are diagonal mass matrices for U -type and D -type quarks respectively. Note that these solutions for the Yukawa coupling matrices no longer hold for $\xi = 1$ we have to treat the $\xi = 1$ case in a separate way. We do not consider that case in this work. Although small ξ is preferred in order to generate the ratio m_b/m_t , $\xi > 1$ region cannot be excluded in general.

III. PRODUCTION OF THE CHARGED HIGGS BOSON AT THE LHC

The relevant interaction lagrangian of the charged Higgs boson production is given by

$$-\mathcal{L} = V_{tb}^* \bar{b}(g_L P_L + g_R P_R)tH^- + H.c., \quad (10)$$

where the couplings are defined by

$$\begin{aligned} g_L &= \sqrt{2\sqrt{2}G_F} \left(m_U \frac{1 + \xi^2}{|1 - \xi^2|} - m_D \frac{2\xi}{|1 - \xi^2|} \right) \left(1 - \frac{1}{4}\epsilon^2(1 + \xi^2) \right) + \mathcal{O}(\epsilon^4), \\ g_R &= \sqrt{2\sqrt{2}G_F} \left(m_U \frac{2\xi}{|1 - \xi^2|} - m_D \frac{1 + \xi^2}{|1 - \xi^2|} \right) \left(1 - \frac{1}{4}\epsilon^2(1 + \xi^2) \right) + \mathcal{O}(\epsilon^4). \end{aligned} \quad (11)$$

The light charged Higgs boson such that $m_{H^\pm} < m_t - m_b$ can be produced through the top quark decay $t \rightarrow bH^\pm$ sequentially after the top quark pair production at the LHC. The cross section of top quark pair production $\sigma(pp \rightarrow t\bar{t}) = \mathcal{O}(1 \text{ nb})$ implies that 10^8 pairs of top quarks will be produced with expected integrated luminosity of 100 fb^{-1} at the LHC. We show the light charged Higgs boson production defined by the cross section times branching ratio, $\sigma(pp \rightarrow t\bar{t}) \cdot \text{Br}(t \rightarrow bH^+)$ in Fig. 1. We use the total cross section for $t\bar{t}$ production as 833 pb for next-to-leading order (NLO) QCD corrections including next-to-leading-log (NLL) resummation [23]. The branching ratio of the top quark decay is constrained by the measurement at the Tevatron, $\text{Br}(t \rightarrow Wb) = 0.94_{-0.24}^{+0.31}$ [22]. The decay of the top quark into a light H^\pm boson has been examined by the CDF collaboration at Tevatron to obtain the exclusion region on the model parameter space with the absence of the observed charged Higgs boson in the MSSM [1] and in the LR model [17]. The parameter space (ξ, m_{H^\pm}) of the LR model is severely constrained by the Tevatron data, even there is a conservative lower bound of $m_{H^\pm} > 145 \text{ GeV}$. The solid parts of the plots are predictions with allowed parameters in the LR model. As a benchmark, the productions of H^\pm in the MSSM are also plotted with varying

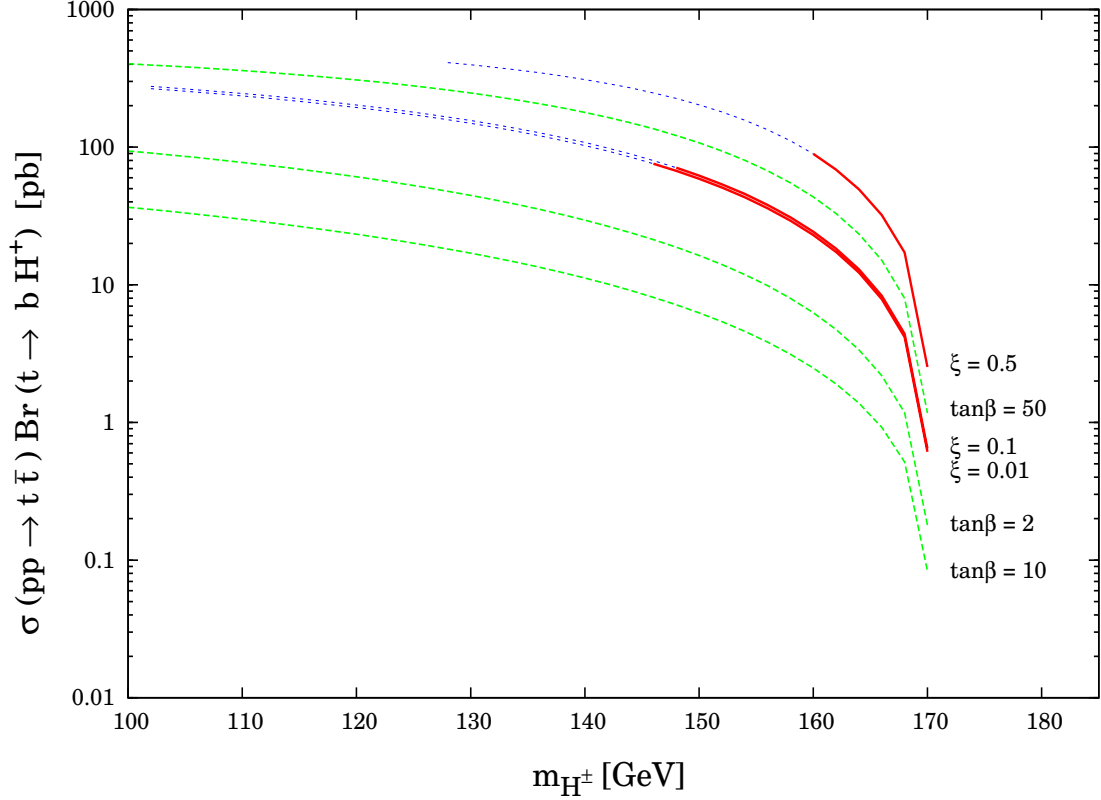


FIG. 1: Production cross sections of a light charged Higgs boson through the sequential decay $pp \rightarrow t\bar{t} \rightarrow t\bar{b}H^+$ at the LHC with respect to H^\pm masses when $m_{H^\pm} < m_t - m_b$.

$\tan\beta$. Yukawa couplings of the LR model have a definite lower bound as ξ varies, so do the production cross sections. We may consider the graph for $\xi = 0.01$ to be the lower bound since the Yukawa couplings are saturated as ξ becomes smaller. The cross section with $\xi = 0.01$ is almost same as that of the 2HD model with $\tan\beta \approx 35$. Thus we find that the productions in the LR model are generically larger than those in the 2HD model unless $\tan\beta$ is large.

If H^\pm is heavier than the top quark, the $gb \rightarrow tH^\pm$ process is the most promising channel for direct production of H^\pm boson at the LHC. We write the scattering amplitude as

$$i\mathcal{M}(g\bar{b} \rightarrow tH^+) = ig_s\bar{b} \left[T_{ab}^c \not{\epsilon}(p_g) \frac{g_L P_L + g_R P_R}{\not{p}_H - \not{p}_b - m_t} + \frac{g_L P_L + g_R P_R}{\not{p}_H + \not{p}_t - m_b} \not{\epsilon}(p_g) T_{ab}^c \right] t, \quad (12)$$

in terms of the Yukawa couplings given in Eq. (11) and obtain the partonic cross section as

$$\hat{\sigma}(g\bar{b} \rightarrow tH^+) = \frac{1}{32\pi\hat{s}} \frac{\sqrt{(\hat{s} - m_t^2 - m_H^2)^2 - 4m_H^2 m_t^2}}{\hat{s} - m_b^2} |\bar{\mathcal{M}}|^2, \quad (13)$$

where the colliding energy is kinematically allowed if $\hat{s} > (m_t + m_H)^2$. The hadronic cross section is given by

$$\sigma(pp \rightarrow g\bar{b} \rightarrow tH^+) = \int dx dy f_g(x) f_b(y) \hat{\sigma}(g\bar{b} \rightarrow tH^+), \quad (14)$$

where f_g and f_b are the parton distribution functions (PDF) for gluon and b -quark respectively. We use the leading order CTEQ6 functions for a gluon and a b -quark PDF in a proton [24]. The QCD factorization and renormalization scales Q are set to be the gb invariant mass, *i.e.*, $\sqrt{\hat{s}}$. The NLO QCD corrections to $gb \rightarrow tH^-$ process in the MSSM has been calculated in Refs. [25, 26] and the next-to-next-to-leading order (NNLO) soft-gluon corrections calculated

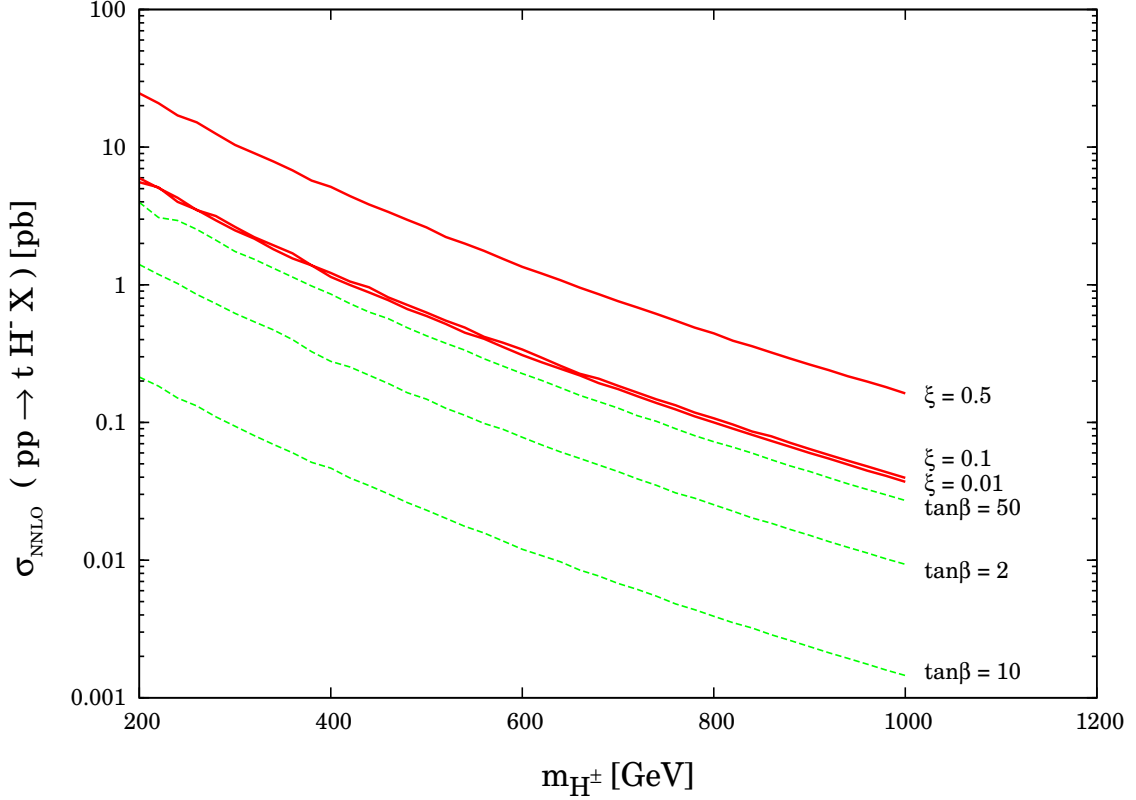


FIG. 2: Cross sections of $pp \rightarrow gb \rightarrow \bar{t}H^+$ process at the LHC including NNLO QCD corrections with respect to the charged Higgs boson masses.

in Ref. [27]. They are shown to be substantial contributions to the production cross section and we include them. Since the QCD corrections are model-independent, we can use the K -factors for the cross section given in Ref. [27] in order to include the QCD corrections for our work. The cross sections including NNLO corrections are depicted in Fig. 2. As a benchmark, the cross sections in the MSSM are also plotted. The running masses for top quark and bottom quark at the scale of m_{H^\pm} have been used in the formula, e.g. $m_t \approx 170$ GeV and $m_b \approx 2.9$ GeV for $m_{H^\pm} = 200$ GeV. The supersymmetric NLO QCD corrections calculated in Ref. [26] are relatively small and depends on the SUSY parameters and we do not include them here. Contribution from the $2 \rightarrow 3$ process, $gg \rightarrow t\bar{b}H^-$ is not considered in this paper. This is considerable, but essentially common process which shows the same trends with a factor two or three smaller than the $gb \rightarrow tH^-$ process in both models. The ξ -dependence of the cross section is shown in Fig. 3. Near $\xi = 1$, the cross section drastically increases and it is saturated as ξ goes far off.

As in the case of the light H^\pm , there is a lower bound for the production cross section $\sigma(pp \rightarrow gb \rightarrow \bar{t}H^+)$ in the LR model. The lower bound value of the cross section of the LR model is close to that of the 2HD model with $\tan\beta = 57$. Thus the cross section of the LR model is generally larger than that in the 2HD model except for large $\tan\beta$ region. We estimate that

$$\frac{(g_L^2 + g_R^2)_{LR}}{(g_L^2 + g_R^2)_{2HD}} \approx \frac{m_t^2 ((1 + \xi^2)^2 / (1 - \xi^2)^2 + 4\xi^2 / (1 - \xi^2)^2)}{m_b^2 \tan^2 \beta + m_t^2 \cot^2 \beta} \gtrsim 2, \quad (15)$$

when $\tan\beta \lesssim 50$. The cross section in the 2HD model increases as $\tan\beta$ increases but suppressed by m_b^2 and the m_t^2 term is suppressed by $1/\tan^2 \beta$. In the LR model, the Yukawa couplings involve the factors of $2\xi/|1 - \xi^2|$ or $(1 + \xi^2)/|1 - \xi^2|$ instead of $\tan\beta$ or $1/\tan\beta$, and they are of order $\mathcal{O}(1)$ or more. Thus the m_t^2 terms in the cross section dominate and the cross section is larger than that in the 2HD model unless $\tan\beta$ is large enough.

IV. DECAY OF THE CHARGED HIGGS BOSON

The produced charged Higgs boson will decay into light particles. The dominant decay channel is $H^+ \rightarrow t\bar{b}$ for $m_{H^\pm} > m_t + m_b$ due to large top quark mass. Another interesting channel is $H^+ \rightarrow \bar{\tau}\nu$ by triggering with a high p_T

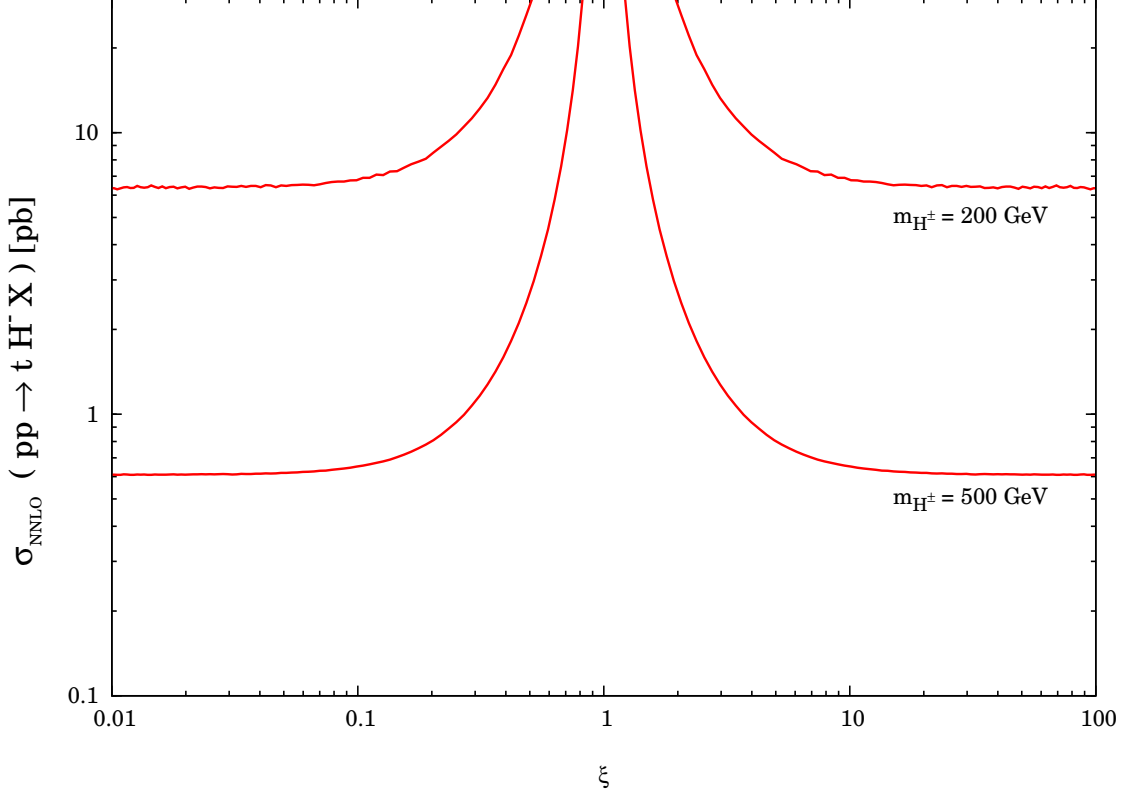


FIG. 3: Cross sections of $pp \rightarrow gb \rightarrow \bar{t}H^+$ process at the LHC including NNLO QCD corrections with respect to ξ .

lepton. We consider the ratio of the decay width for $H^+ \rightarrow \bar{\tau}\nu$ to that for $H^+ \rightarrow t\bar{b}$ in the LR model and 2HD model. In the LR model, we have

$$\frac{\Gamma(H^+ \rightarrow \bar{\tau}\nu)}{\Gamma(H^+ \rightarrow t\bar{b})} = \frac{1}{3|V_{tb}|^2 (1 - m_t^2/m_{H^\pm}^2)} \frac{m_\tau^2}{m_t^2} \frac{4\xi^2}{1 + 6\xi^2 + \xi^4}, \quad (16)$$

while the ratio in the 2HD model is given by

$$\frac{\Gamma(H^+ \rightarrow \bar{\tau}\nu)}{\Gamma(H^+ \rightarrow t\bar{b})} = \frac{1}{3|V_{tb}|^2 (1 - m_t^2/m_{H^\pm}^2)} \frac{m_\tau^2 \tan^2 \beta}{m_t^2 \cot^2 \beta + m_b^2 \tan^2 \beta}, \quad (17)$$

where m_b/m_{H^\pm} , $m_\tau/m_{H^\pm} \ll 1$ and QCD corrections are ignored. The ratios are depicted in Fig. 4. We find that the ratio can be sizable in the 2HD model as $\tan \beta$ increases. It is as large as more than 10 % when $\tan \beta > 10$, while the ratio is always negligible in the LR model by suppression of m_τ^2/m_t^2 . Therefore we can discriminate the underlying Higgs structure of the charged Higgs boson by measuring the ratio $\Gamma(H^+ \rightarrow \bar{\tau}\nu)/\Gamma(H^+ \rightarrow t\bar{b})$ in the most interesting region of parameter space. When $m_{H^\pm} < m_t - m_b$, the tau channel dominates like in the 2HD model.

V. DETECTION OF THE CHARGED HIGGS BOSON

As shown in the previous section, the H^\pm boson in the LR model mostly decays into $t\bar{b}(\bar{t}b)$ when $m_{H^\pm} > m_t + m_b$. The decay product contains two top quarks. We require one of the top quark to decay semileptonically, $t \rightarrow Wb \rightarrow l\nu b$, and the other hadronically, $t \rightarrow Wb \rightarrow jj'b$, for triggering and reconstruction of the top quark as well as the charged Higgs boson. The promising final states inside the detector are given by

$$gb \rightarrow tH^\pm \rightarrow ttb \rightarrow W^+W^-bbb \rightarrow l\nu jj'bbb, \quad (18)$$

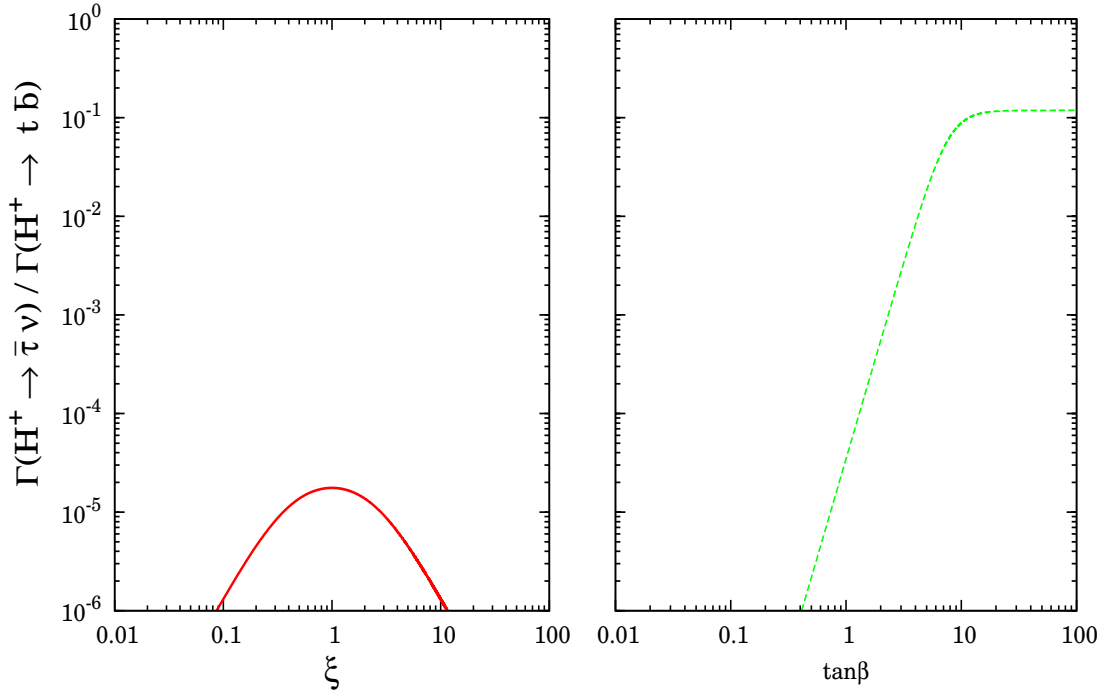


FIG. 4: The ratios $\Gamma(H^+ \rightarrow \tau \nu) / \Gamma(H^+ \rightarrow t \bar{b})$ with respect to ξ and $\tan\beta$ in the LR model and the 2HD model respectively.

which involve three b -jets and an isolated lepton. The main background in the SM is coming from the $t\bar{t}$ pair production involving another b jet or other jets. The Monte Carlo simulations for the detection of the charged Higgs boson in the MSSM through $H^\pm \rightarrow tb$ have been performed by ATLAS [28] and CMS [29] groups to estimate the discovery potentials of H^\pm . The essential improvement is expected in the signal reconstruction if the b -tagging efficiency increases in the future. Their results show that the charged Higgs can be discovered up to 300 GeV at low luminosity period of the LHC with the integrated luminosity $\int \mathcal{L} \sim 30 \text{ fb}^{-1}$. The discovery limit can be raised to be 400 GeV for high $\tan\beta$ (> 25). It is hard to discover the charged Higgs of the 2HD model with the mass above 400 GeV. On the other hand, the production cross sections of H^\pm in the LR model are generically larger than those in the 2HD model. The larger number of produced H^\pm bosons due to the larger production cross section indicates an improvement of the signal-to-background ratio since the background events are the SM processes. We expect the better visibility of the charged Higgs boson in the LR model, although no Monte Carlo study for H^\pm has been done yet in the LR model.

VI. CONCLUDING REMARKS

In this work, we have calculated the production cross sections of the charged Higgs boson in the LR model at the LHC. Observation of a charged Higgs boson is a clear evidence of existence of new physics beyond the SM. We see that the production cross sections of H^\pm in the LR model have lower bounds depending upon the charged Higgs mass. The cross sections in the LR model are generically larger than those of the 2HD model in the most region of $\tan\beta$ and the better visibility of H^\pm is expected through $H^\pm \rightarrow tb$ channel. We find that the decay into $\tau\bar{\nu}$ channel is strongly suppressed in the LR model due to the smallness of m_τ^2/m_t^2 . Combining the cross section and the ratio $\Gamma(H^+ \rightarrow \tau\nu)/\Gamma(H^+ \rightarrow t\bar{b})$, therefore, we can discriminate the LR model from the 2HD model as the underlying physics in the charged Higgs sector. If the production cross section of H^\pm is lower than the minimal value predicted by the LR model shown in Fig. 2, we can conclude that the LR model is not the underlying physics. When the H^\pm boson is observed with the production cross section large enough, it may be the ingredient of either the LR model or the 2HD model with large $\tan\beta$. In that case, the ratio $\Gamma(H^+ \rightarrow \tau\nu)/\Gamma(H^+ \rightarrow t\bar{b})$ close to 0 indicates the LR model and the ratio of 10 % indicates the 2HD model with large $\tan\beta$.

In conclusion, the charged Higgs sector can be crucially tested in the production and decay at the LHC. We study the LHC phenomenology of the charged Higgs boson in the LR model compared with that in the 2HD model.

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- [1] A. Abulencia *et al.*, CDF Collaboration, Phys. Rev. Lett. **96**, 042003 (2006).
 - [2] The LEP Collaborations ALEPH, DELPHI, L3 and OPAL, LEP working group for Higgs boson searches, hep-ex/0107031; Euro. Phys. J. C **47**, 547 (2006).
 - [3] F. Borzumati and A. Djouadi, Phys. Lett. B **549**, 170 (2002).
 - [4] T. Browder, *Rare B Decays with “Missing Energy”*, talk delivered at the 33rd International Conference on High Energy Physics (ICHEP 06), Moscow, Russia, 26 Jul - 2 Aug 2006.
 - [5] W.-S. Hou, Phys. Rev. D **48**, 2342 (1993).
 - [6] A. C. Bawa, C. S. Kim and A. D. Martin, Z. Phys. C **47**, 75 (1990).
 - [7] V. D. Barger, R. J. N. Phillips and D. P. Roy, Phys. Lett. B **324**, 236 (1994); S. Moretti and K. Odagiri, Phys. Rev. D **55**, 5627 (1997).
 - [8] D.-W. Jung, K. Y. Lee and H. S. Song, Phys. Rev. D **70**, 117701 (2004).
 - [9] A. Belyaev, D. Garcia, J. Guasch and J. Sola, JHEP **06**, 059 (2002).
 - [10] ATLAS Collaboration, Report No. CERN/LHCC/99-15 (1999) Vol. 2.
 - [11] CMS Collaboration, Report No. CERN/LHCC/94-38 (1994).
 - [12] R. N. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 2558 (1975); J. C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974); Erratum *ibid.* D **11**, 703 (1975); For reviews, see R. N. Mohapatra, *Unification and Supersymmetry* (Springer, New York, 1986).
 - [13] M. Czakon, J. Gluza and M. Zralek, Phys. Lett. B **458**, 355 (1999).
 - [14] K. Cheung, Phys. Lett. B **517**, 167 (2001).
 - [15] J. Chay, K. Y. Lee and S.-h. Nam, Phys. Rev. D **61**, 035002 (1999).
 - [16] J. Erler and P. Langacker, Phys. Lett. B **456**, 68 (1999).
 - [17] D.-W. Jung and K. Y. Lee, Phys. Rev. D **76**, 095016 (2007).
 - [18] N. G. Deshpande, J. F. Gunion, B. Kayser and F. Olness, Phys. Rev. D **44**, 837 (1991).
 - [19] K. Kiers, M. Assis and A. A. Petrov, Phys. Rev. D **71**, 115015 (2005).
 - [20] O. Khasanov and G. Perez, Phys. Rev. D **65**, 053007 (2002).
 - [21] J. F. Gunion, J. Grifols, A. Mendez, B. Kayser and F. Olness, Phys. Rev. D **40**, 1546 (1989).
 - [22] W.-M. Yao *et al.*, *Review of Particle Physics*, J. of Phys. G **33**, 1 (2006).
 - [23] R. Bonciani *et al.*, Nucl. Phys. **B529**, 424 (1998).
 - [24] S. Kretzer, H. L. Lai, F. I. Olness and W. K. Tung, Phys. Rev. D **69**, 114005 (2004).
 - [25] S.-h. Zhu, Phys. Rev. D **67**, 075006 (2003).
 - [26] T. Plehn, Phys. Rev. D **67**, 014018 (2003); E. L. Berger, T. Han, J. Jiang and T. Plehn, Phys. Rev. D **71**, 115012 (2005).
 - [27] N. Kidonakis, JHEP **05**, 011 (2005).
 - [28] K. A. Assamagan, Acta Phys. Pol. B **31**, 863 (2000); K. A. Assamagan and N. Gollub, Euro. Phys. J. C **39**, s25 (2004).
 - [29] S. Lowette, J. Heyninck and P. Vanlaer, Report No. CMS CR 2004/031.